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A Review of SCATHA Satellite Results: Charging and Discharging

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This report summarizes the major results from the SCATHA (P78-2) satellite charging monitors and discharge detectors. The data show that surface chargi[illegible]ear synchronous altitudes, occurs preferentially in the midnight to loc[illegible] morning sectors, as expected. Evidence for bulk charging by energetic electrons is also observed. The material-charging data show that there was a marked increase in bulk conductivity of solar-illuminated Kapton with exposure time in the space vacuum. Teflon accumulated a permanent

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charge that slowly increased with time, and a quartz "cloth" material charged to higher than expected levels; some of these material effects have now been simulated in the laboratory. The statistical picture of the surface charging and the resultant discharges and noise generation show a close association with each other. Some of the discharges <u>are</u> ascribed to possible bulk charging. The signal amplitudes of the discharges are discussed and the temporal character of the discharge signal is shown for a few cases. The results represent a new baseline in our understanding of satellite charging and its effects.

CONTENTS

FIGURES

I. INTRODUCTION

Satellites in near-synchronous orbit are known to charge and to experience malfunctions that have been ascribed to charging (see Refs. 5, 9, 10, 20, and 30). The SCATHA (Spacecraft Charging at High Altitudes) satellite was specifically instrumented to monitor and study the charging phenomena, to correlate the charging levels with the plasma environment, and to detect the occurrence of discharges on the satellite (Refs. 6, 11, 20, 31, and 34). The SCATHA satellite and instrumentation have been described by Stevens and Vampola (Ref. 31), and the surface charging and discharge detection experiments have been described in greater detail in several published reports (Refs. 1, 11, 13, 14, 24, 26, and 27), so we will not provide a detailed description of them in this report. Where necessary, instrumental parameters are given in the discussion.

The electrical properties of spacecraft insulating materials are measured by a Satellite Surface Potential Monitor (SSPM) from The Aerospace Corporation (Refs. 24 and 25). This experiment measures the potential of six different materials relative to satellite-structure ground. Some of these materials undergo changes when exposed to the particle and radiation environments in space (Refs. 21 through 23). The ability to predict how these changes occur as a function of time is needed if one is to extend the reliability and mission life of spacecraft. The SCATHA satellite measurements have shown that the electrical conductivity of Kapton changed dramatically in the near-geosynchronous orbit (Ref. 22). The Teflon measurements showed evidence of charge retention and buildup with time, and the quartz cloth thermal blankets charged to higher levels than expected; such results must be understood before these materials are used on new spacecraft. Consequently, a laboratory program was initiated at The Aerospace Corporation to measure and explain these effects (Refs. 15, 16, 17, and 21).

Discharges are one of the effects of charging, and they cause electrical interference (noise) in satellite systems (Refs. 9, 10, 20, 27, and 30). Sometimes they are more than a nuisance and can cause permanent damage or require constant and expensive monitoring of satellite operations. The SCATHA satellite has provided some information concerning the occurrence and severity of such discharges. These data are provided by two sensors: the Transient Pulse Monitor (TPM) from Stanford Research Institute (SRI) (Ref. 1), and the Charging Electrical Effects Analyzer (CEEA) from The Aerospace Corporation (Ref. 13 and 14). We will emphasize the results from the Aerospace instrument in this report.

The majority of noise pulses detected on the SCATHA satellite have been ascribed to normal satellite operations (Refs. 13 and 14). The number of discharges, measured with the Aerospace experiment, that are thought to be related to natural charging is of the order of ~40 in 1.2 years of data. Some may have been missed because of the mode of operation that the experiment was in for part of the time. Also, the operational mode did <u>not</u> always allow a detailed time profile of the discharge pulses to be measured (Ref. 11). The majority of the natural discharges occurred in regions where surface charging of dielectric materials was observed. A few occurred when no surface charging was observed, and these are ascribed to bulk charging (Refs. 11, 19, 28, 29, 33, and 35).

These results are presented in some detail below and are an attempt to combine in one document both the results from The Aerospace Corporation measurements on the SCATHA satellite and results from complementary laboratory studies.

II. MATERIALS EFFECTS

The SSPM was flown on the P78-2 SCATHA satellite (Refs. 18 and 24) to study the electrical behavior of typical spacecraft insulating materials in the space environment. The P78-2 satellite is a spin-stabilized satellite whose spin axis is maintained perpendicular to the satellite-sun line. Two Kapton samples are mounted in such a way that they rotate into and out of the sunlight. A third Kapton sample and silvered Teflon and quartz-fabric samples were mounted in the shadow of the spacecraft (Ref. 26). All material surface potentials were measured relative to the spacecraft-structure ground. (For a description of the technique used, see Refs. 24, 25, 26, and 31).

The first surprising result was the measurement of a relatively high level of charging on the quartz fabric. This fabric was mounted on Teflon backed with silver, and a small hole was cut in the Teflon to expose the electric field from the fabric to the backside sensor (Ref. 26). Figure 1 shows the charging levels of the quartz fabric (and other materials) during a natural charging event on 24 April 1979: the fabric charged to over 3 kV. Laboratory measurements by Belanger and Eagles (Ref. 3), prior to SCATHA's launch, had indicated that this material would not charge significantly above a few hundred volts in the space environment. Other tests, however, had indicated the fabric might indeed charge to high levels (Ref. 32). At the launch of SCATHA the materials science community was split in its opinion concerning whether the actual samples being flown would charge or not. In fact, the quartz fabric had been chosen by one satellite program as a thermal blanket because it had not charged to high levels in laboratory tests.

An Aerospace laboratory test program was set up to find out why there was such a difference between quartz-fabric charging levels on orbit (Ref. 21) and those observed in the laboratory (Ref. 3). Figure 2 shows the charging response of the quartz fabric when irradiated by a 6-keV electron beam of different current densities. As seen in the figure, the lower current beams charged the sample to the higher voltages for longer periods. The 0.08 nA/cm^2 beam that charged the sample to the highest value in this test was about two

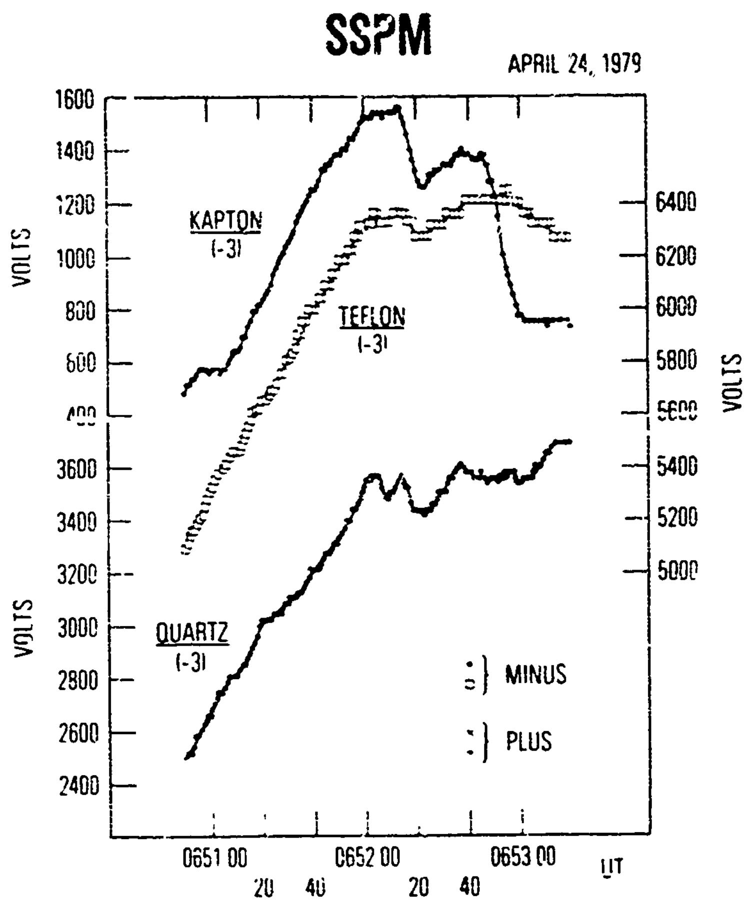

Fig. 1. Kaption, Teflon, and Quartz-Fabric Charging Levels on the SCATHA (P78-2) Satellite during the 24 April 1979 Charging Event (after Ref. 23)

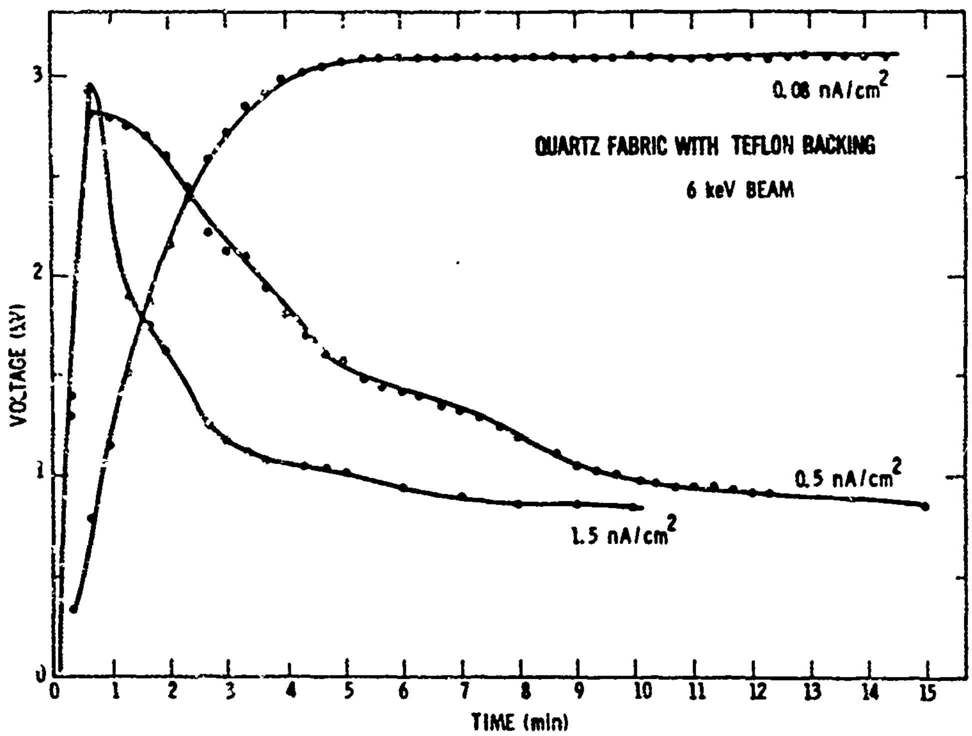

Fig. 2. Typical Response of a Quartz-Fabric Sample with Silvered Teflon Backing under Laboratory Electron Irradiation (after Ref. 15)

orders of magnitude lower in current than the beams used in the Belanger and Eagles study (Ref. 3).

Basically, it was found that the charging level of the quartz fabric initially rose to a relatively high value, with the rate of charging greater for higher incident current. Then, the charging level decreased to a steady-state value of a few hundred volts, with the most rapid decrease occurring for the higher incident currents. Thus, the early laboratory results (Ref. 3) were correct for the steady state but did not show that the rate of both charging and discharging was sensitive to incident-current density. With the very low current densities experienced in the natural environment, such as the 0.1 nA/cm^2 estimated for the 24 April event (Ref. 21), the quartz fabric can charge to high levels relative to the satellite ground for significant periods of time.

Another interesting result from the SSPM experiment on SCATHA was the observation that the Teflon samples showed a permanent potential offset after only a few days on orbit. By the time of the 24 April charging events shown in Fig. 1, the Teflon sample showed a -2000-V offset, an offset not due to surface charging. We studied the Teflon bulk-charge buildup using the SCATHA data, by plotting the Teflon potential as a function of time (Fig. 3). These data were taken at local noon, where the probability of surface charging is observed to be a minimum (Ref. 23). There is an obvious gradual increase in the minimum Teflon potential with time. On top of this gradual increase are superimposed rather large short-duration potential jumps, which occur over a period of about a day. Some are associated with satellite attitude maneuvers, which cause the Teflon to be illuminated for a short time, and others were caused by large energetic-particle enhancements (Ref. 22).

Recent calculations of the levels of potential expected from imbedded energetic electrons in Teflon give results in agreement with the observed potentials (Ref. 28). Some early laboratory studies (Ref. 36) suggested a model for Teflon discharge events in which the charges from a charge-deposition layer would flow through a localized channel to the back surface. Reagan et al. (Ref. 28) indicated they do not expect the electric field inside

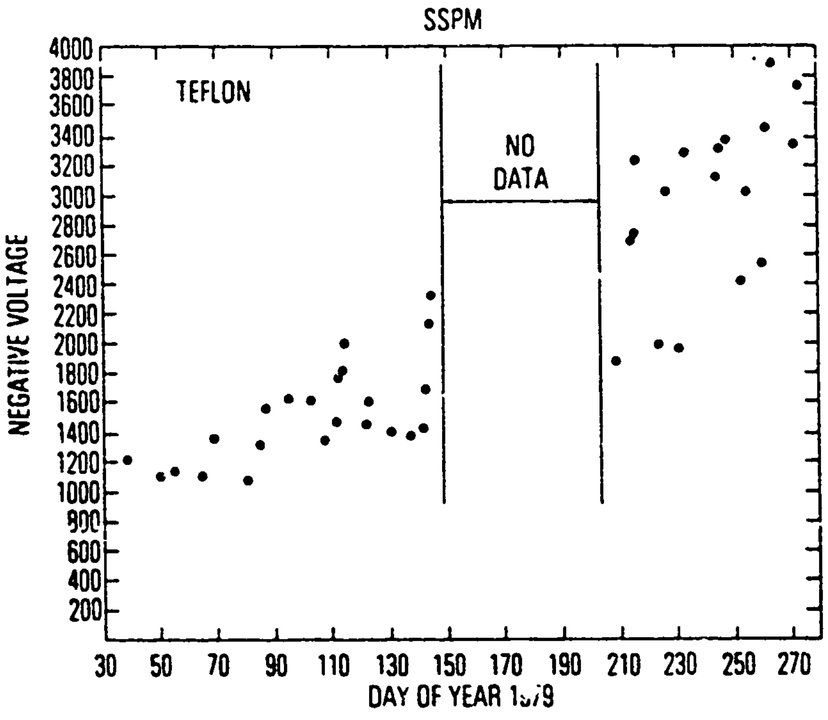

Fig. 3. Teflon Potentials (in Volts) Taken when the P78-2 Satellite was Near Local Noon. These variations in voltages are not due to surface charging (after Ref. 23).

the Teflon potential to reach dielectric breakdown levels, but that micrometeorites or heavy cosmic rays penetrating the material may create a breakdown channel.

Another effect that has been estimated for Teflon is the enhancement in radiation-induced conductivity enhancement (Ref. 29). Calculations, based on measured energetic-electron dose rates, show that the conductivity of Teflon can be enhanced over its intrinsic conductivity by substorm and magnetic storm increases in the particle fluxes. This would explain a modulation of the Teflon potential by such magnetospheric events.

At times other than magnetospheric storms, when the Teflon is shadowed its resistivity is very large and the embedded charges from electrons with energy $\lesssim$150 keV cannot easily migrate. It is expected that the charges would build up, increasing the potential until the electric fields are strong enough to pull the charge out of the material as fast as it is produced. As Fig. 3 shows, such an equilibrium potential was not reached in the first 250 days on orbit. More recent data indicate that the potential has reached a limit somewhat below 4000 V. This limit may be artificial because of the attitude maneuver effect previously mentioned.

So far, the last material change noted on orbit was the ever-decreasing level of charging of some of the Kapton samples (Refs. 22 and 23). This was first noted by comparing the charging levels of Kapton during similar charging events separated in time by several months. The Kapton samples in question are on the sides of the spacecraft and are exposed to the sun every spin period (Refs. 25 and 31). The charging levels of these samples are compared with the potential of an isolated gold-plated conductor as a reference. As a second diagnostic, the bulk-current density through the Kapton is also measured (Ref. 21).

Figure 4 shows the measured bulk currents, as a function of surface potential, for the 10 June 1980 and 28 March 1979 events; these currents were unilluminated in the laboratory. The bulk current measured on orbit was more than three orders of magnitude greater than the laboratory values. The June 1980 current, at low potential, is larger by nearly a factor of three than the

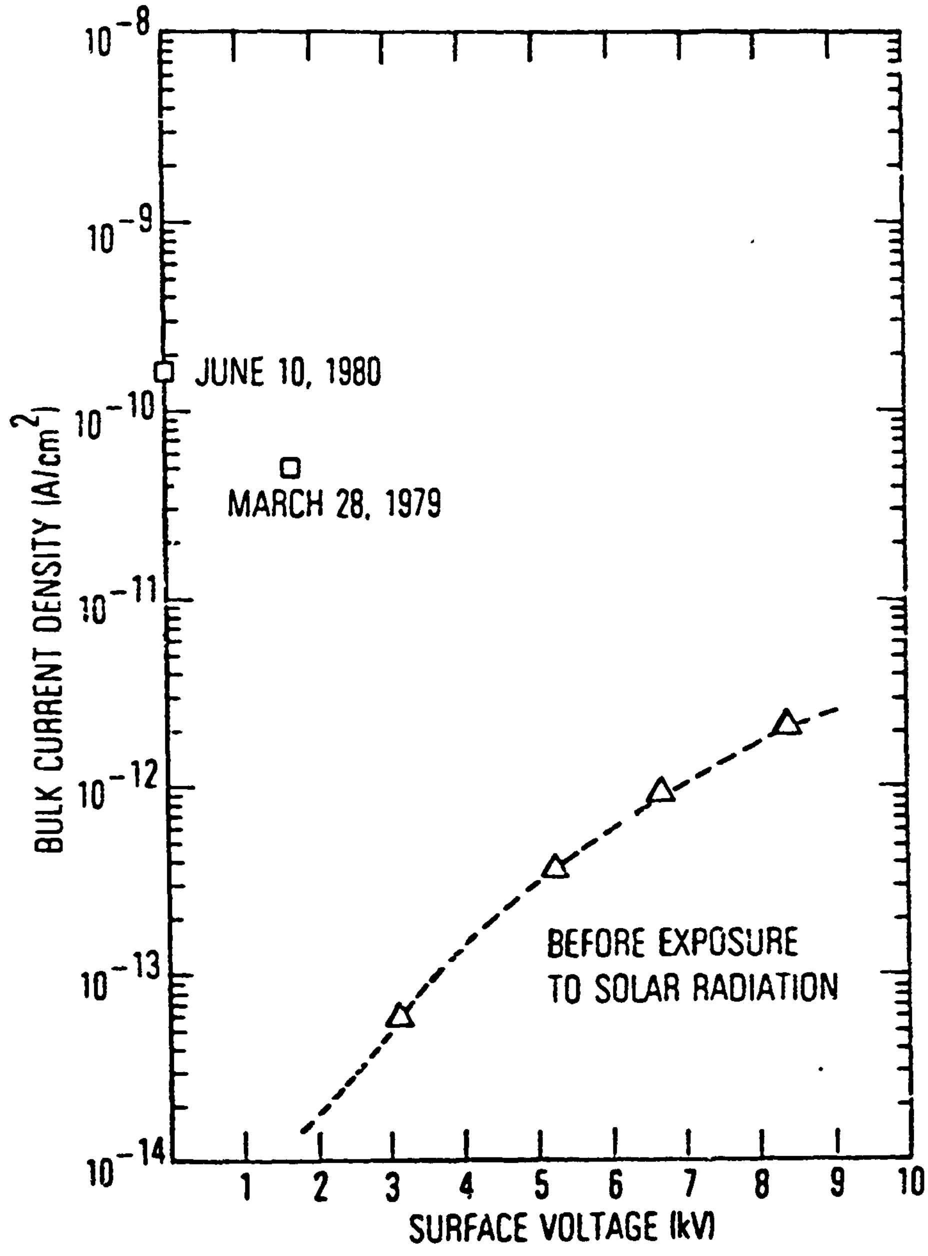

Fig. 4. Bulk Kapton Current Measured on Orbit (10 June 1980 and 28 March 1979) and in the Laboratory (after Ref. 18)

earlier March 1979 value at ~1.7 kV potential. This suggested that solar illumination of the Kapton samples on the sides of the vehicle had caused a conductivity increase, and that the level of conductivity was probably increasing continuously with time.

This was tested by comparing the Kapton voltage to the gold sample voltage for a large body of data (from 7 February 1979 to 17 February 1980). The result is shown in Fig. 5, where each point represents the ratio of the maximum Kapton voltage to the maximum gold voltage for each 24-h period. Gold was assumed to be a space-stable reference, and any trends in the ratio were attributed to changes in the Kapton characteristics, specifically its conductivity. Figure 5 shows the result for the smaller Kapton sample (area ~160 cm^2). The results were identical for the large sample (area ~ 830 cm^2), indicating sample area is not a factor. The solid line is an exponential regression line with the slope shown. The Kapton samples show an ever-lower maximum potential with increasing time. The e-folding time for the decrease in the ratio is ~92 days (Ref. 24). The fact that both samples behaved the same means these changes in bulk conductivity are representative of Kapton itself. During this same period the shadowed Kapton sample on the top of the satellite showed no such conductivity changes, so it was concluded that the solar UV caused the conductivity change (Refs. 22 and 24).

Such results had been suggested by some early laboratory tests (Refs. 2 and 4) in which the conductivity of Kapton was seen to rise with increasing temperature, with increasing voltage impressed on the sample, and with exposure to light from a sun simulator. The <u>dark</u> conductivity of Kapton was found to increase by ~2 orders of magnitude in the first hour, after exposure to a "one-sun" illumination, and then the rate of increase slowed with extended exposure. Similar results were also obtained with the Teflon and quartz fabric, but the conductivity increases were orders of magnitude less than those of Kapton. Adamo and Nanevicz (Ref. 2) also examined the photoconductivity of Kapton as a function of UV wavelength and found its increase in conductivity to be greatest for light with wavelengths from 450 to 524 nm.

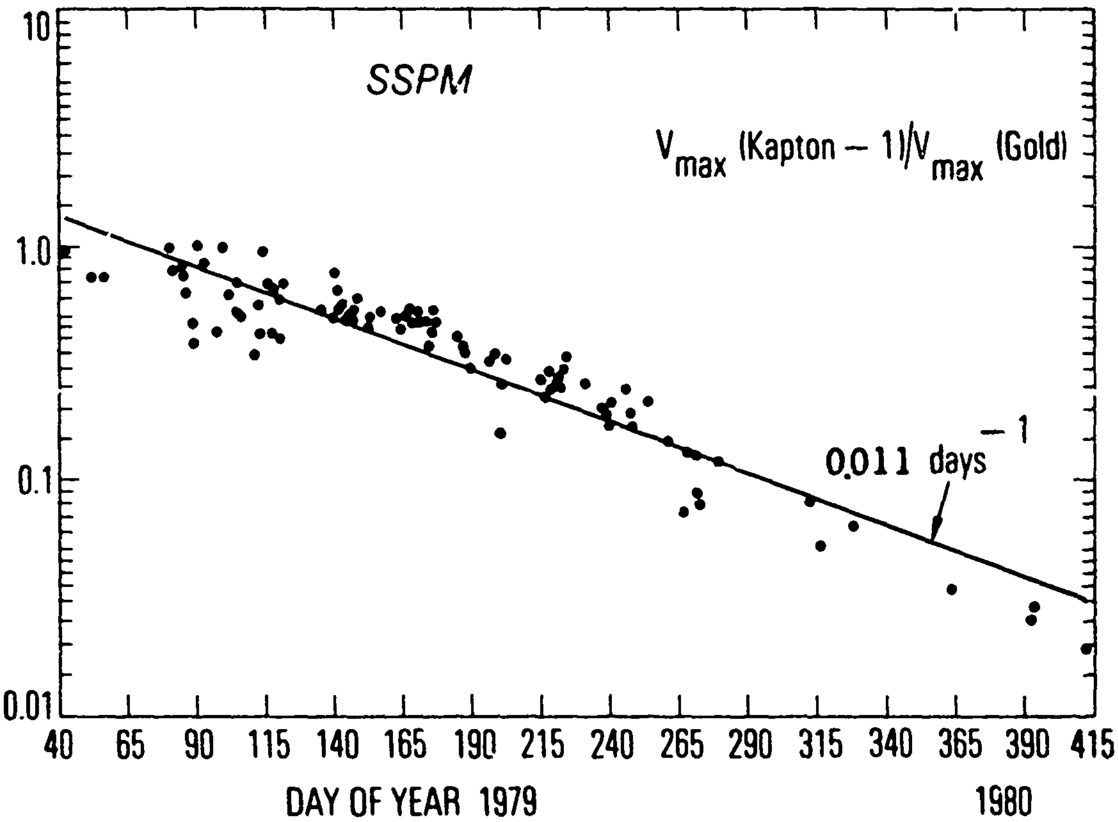

Fig. 5. Logarithmic Ratios of Kapton Voltage to Gold Conductor Voltage with Time. Both samples were on the SSPM-1 instrument mounted on the P78-2 bellyband, with 50% solar exposure. Early ratios were normalized to 1 (after Ref. 21).

After the SCATHA Kapton results were seen, measurements were made at The Aerospace Corp. (Refs. 15 and 16) on samples identical to the SCATHA samples in a duplicate of the SCATHA SSPM instrument. The tests were carried out using simulated solar and particle radiation (Refs. 16, 17, 18, and 21). The bulk dark current of Kapton was measured as a function of the surface potential. The Aerospace tests (Refs. 15, 18, and 21) confirmed the SRI results (Refs. 2 and 4), which showed that the bulk dark current of Kapton was about three orders of magnitude higher after UV exposure than before. It should be noted here that we do not mean the instantaneous photoconductivity of the material during UV exposure, but an enhancement in the dark conductivity of the material after it has been illuminated. Exposure to UV for a short time caused a permanent change in the dark bulk conductivity as long as the material was in vacuum.

This dark conductivity enhancement was reduced if the sample was exposed to air (Refs. 18 and 21). This is shown in Fig. 6, where a profile of the bulk dark current versus voltage is plotted for (1) the unilluminated sample, (2) a sample that was exposed to "one sun" for 60 min, and (3) that sample after it was exposed for an additional 28 min. After the second illumination and dark-current measurement, the sample was exposed to atmosphere for 15 min, after which a new dark-conductivity profile was run in vacuum (curve 4 in Fig. 6). This was followed by sample illumination for 45 min (curve 5), whereupon the dark current again increased to the previous (curve 3) value. So, exposure to air partially "quenched" the conductivity enhancement, but illumination by "one-sun" UV in vacuum caused the dark current to increase again.

Why does the Kapton dark conductivity permanently increase in a vacuum after exposure to UV, and why does it quench when exposed to air? A partial answer to this question is given by the laboratory tests. As mentioned earlier, Adamo and Nanevicz (Ref. 2) showed that the Kapton photoconductivity was enhanced most effectively by light in the wavelength range of 450 to 524 nm. Mizera et al. (Ref. 21) did a similar test for dark conductivity, in which they showed that indeed the largest bulk current was provided when both 2-mil and 5-mil Kapton samples had been exposed to "solar" light through a filter having a peak transmission near 502 nm. A shorter-wavelength light,

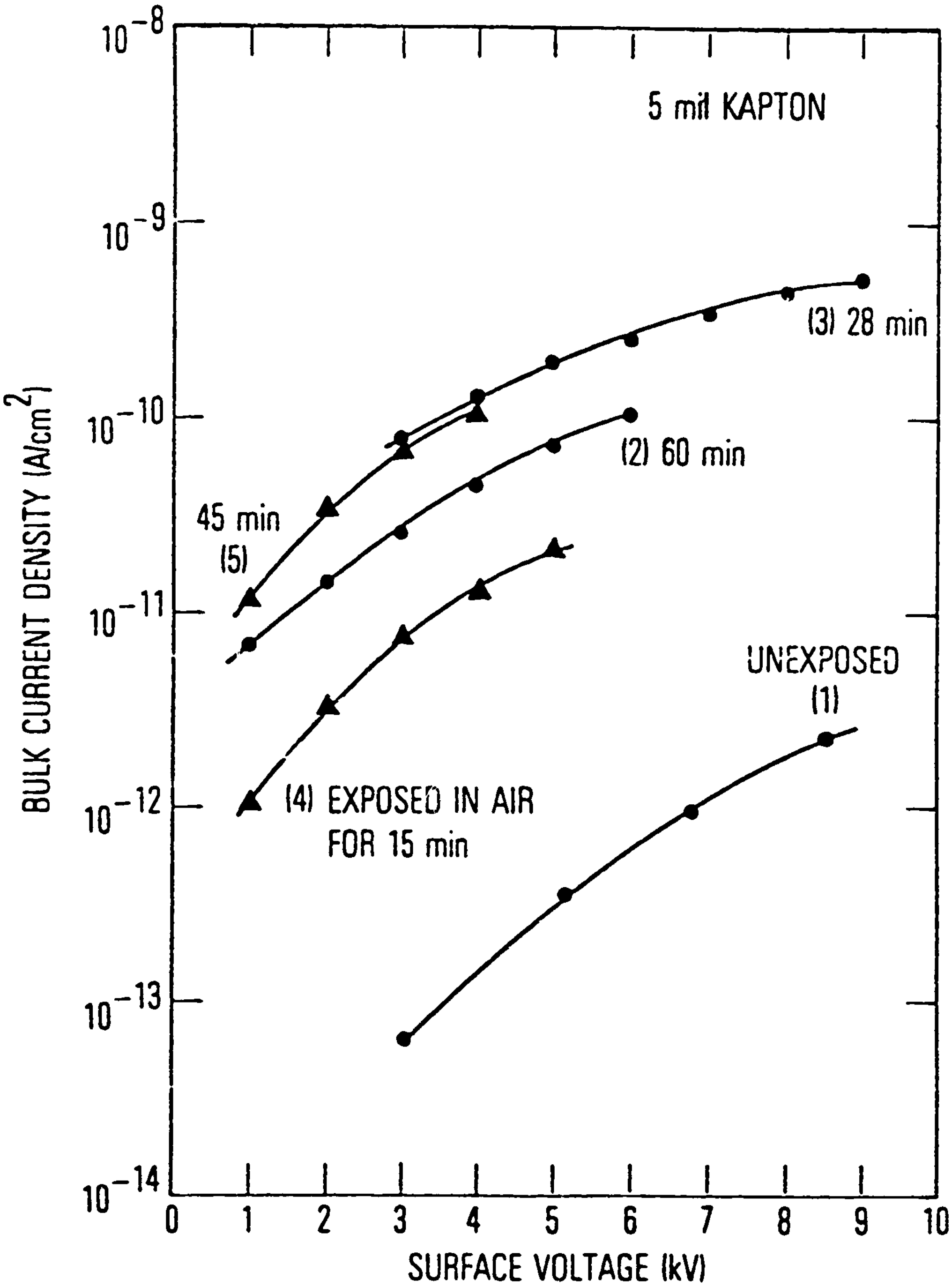

Fig. 6. Laboratory Simulation of the Photo-Induced Enhancement of Kapton Conductivity (after Ref. 18)

425 nm, produced the smallest response, and the 560-nm wavelength produced an intermediate response. Apparently the shortest wavelength, which just starts to penetrate the material, produces both the maximum photoconductivity and permanent conductivity change in Kapton (Refs. 15, 17, 18, and 21).

To study the photochemistry of what had occurred in the Kapton, we exposed samples to various gases after raising their dark conductivity by means of UV illumination (Refs. 7 and 18). Argon, dry N_2, and dry air were used, but only dry air caused a quenching of the enhanced conductivity. On the basis of this result it was suggested (Ref. 18) that oxygen was responsible for the quenching.

III. CHARGING AND DISCHARGING

Beyond the material changes discussed above, there are also the on-orbit studies of the occurrence of charging and discharging, as well as studies of the possible relationships between the two conditions. The charging and discharging statistics have been accumulated for more than one year of SCATHA data (Refs. 12, 13, 14, 23, 24, and 25) and are summarized in Figs. 7, 8, 9, 10, and 11. The study of charging and discharging relationships is based on a few "case" or "event" studies where all possible information is brought to bear for a limited time period (usually tens of minutes) (see Fig. 13, below).

The statistical occurrence of surface charging has been examined for Kapton, gold-plated magnesium, and optical solar reflectors (OSRs) (Ref. 17). While the probability of charging to levels >100 V relative to the SCATHA satellite-structure ground was highly material-dependent (maximum probability ranged from 2 to 5% for OSRs to >50% for Kapton during magnetically disturbed times), the local-time distributions for all materials were essentially the same. This local-time dependence is summarized by means of the Kapton results in Figs. 7 and 8. The dominant charging region is the premidnight to prenoon sector of the near-synchronous region. The >50% probability of >100-V charging reaches a maximum in the outer regions of the SCATHA orbit near local morning, whereas the >1000-V charging occurred at lower altitudes in the premidnight region. The high levels of charging (>500 V) have a relatively low probability of occurrence ($\lesssim$10%) and exist only during magnetically disturbed periods (Kp > 2+). Outside the 10% probability region for >100-V charging (Fig. 8), differential spacecraft charging is not expected to be important (Ref. 23).

Twenty days of Transient Pulse Monitor (TPM) (Refs. 1 and 27) data from charging events were examined and compared with the maximum Kapton charging levels and with the statistical charging picture. The Kapton charging at the times of the TPM responses varied from 100 to 10,000 V, with most events being >500 V. These TPM events are plotted with local time vs. distance in Fig. 9. The regions of >50% probability of >100-V charging and high charging are also

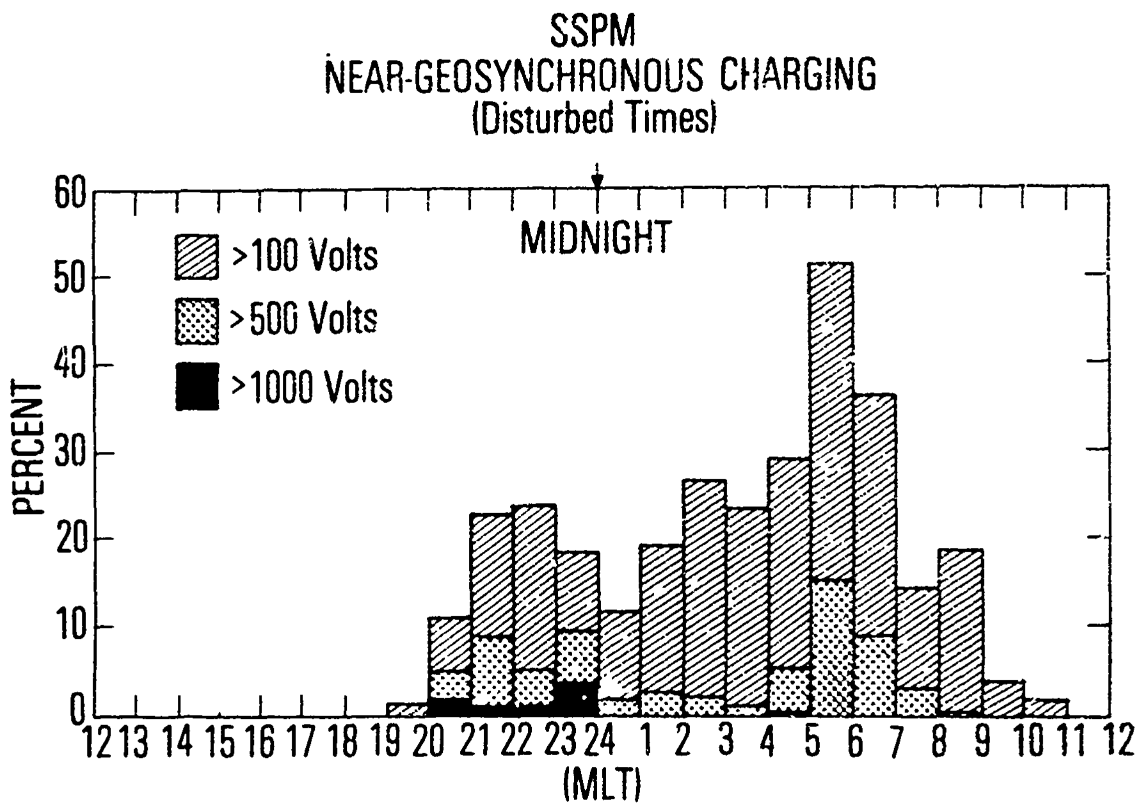

Fig. 7. One-Hour Local-Time Histograms of Charging Probabilities for the Near-Geosynchronous Altitudes (after Ref. 23)

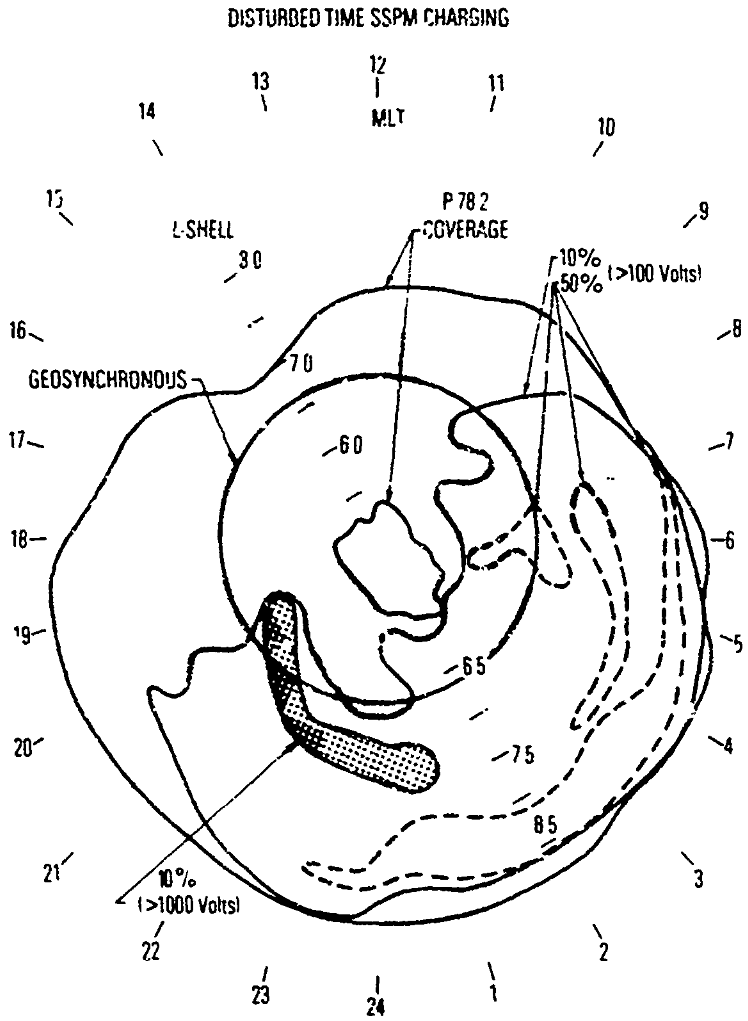

Fig. 8. Polar Plot of the P78-2 Coverage in L-Shell and MLT Space for Days 38 through 273, 1979. The gray areas represent total coverage of less than 1.5 h. The dashed contours represent charging of Kapton with >50% probability of reaching -100 V during disturbed times. The cross-hatched contour represents a 10% probability of charging to >-1000 V (after Ref. 23).

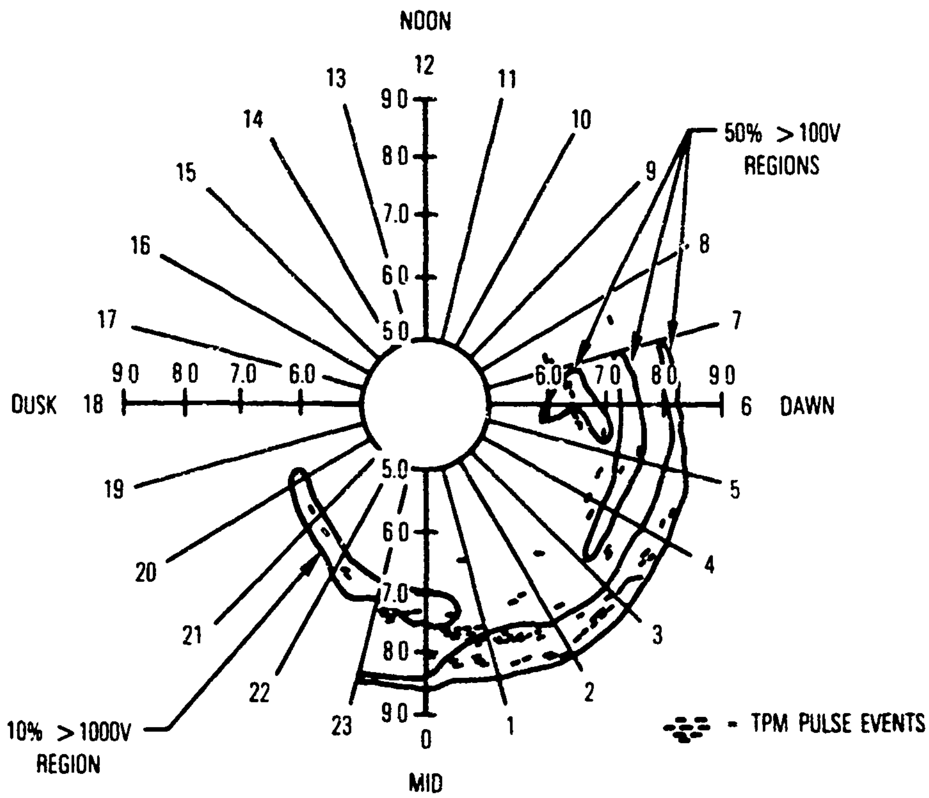

Fig. 9. Polar Plot of the Regions of High Probability of Charging and High Charging (see Fig. 8) and Transient Pulse Monitor Responses during Charging Events

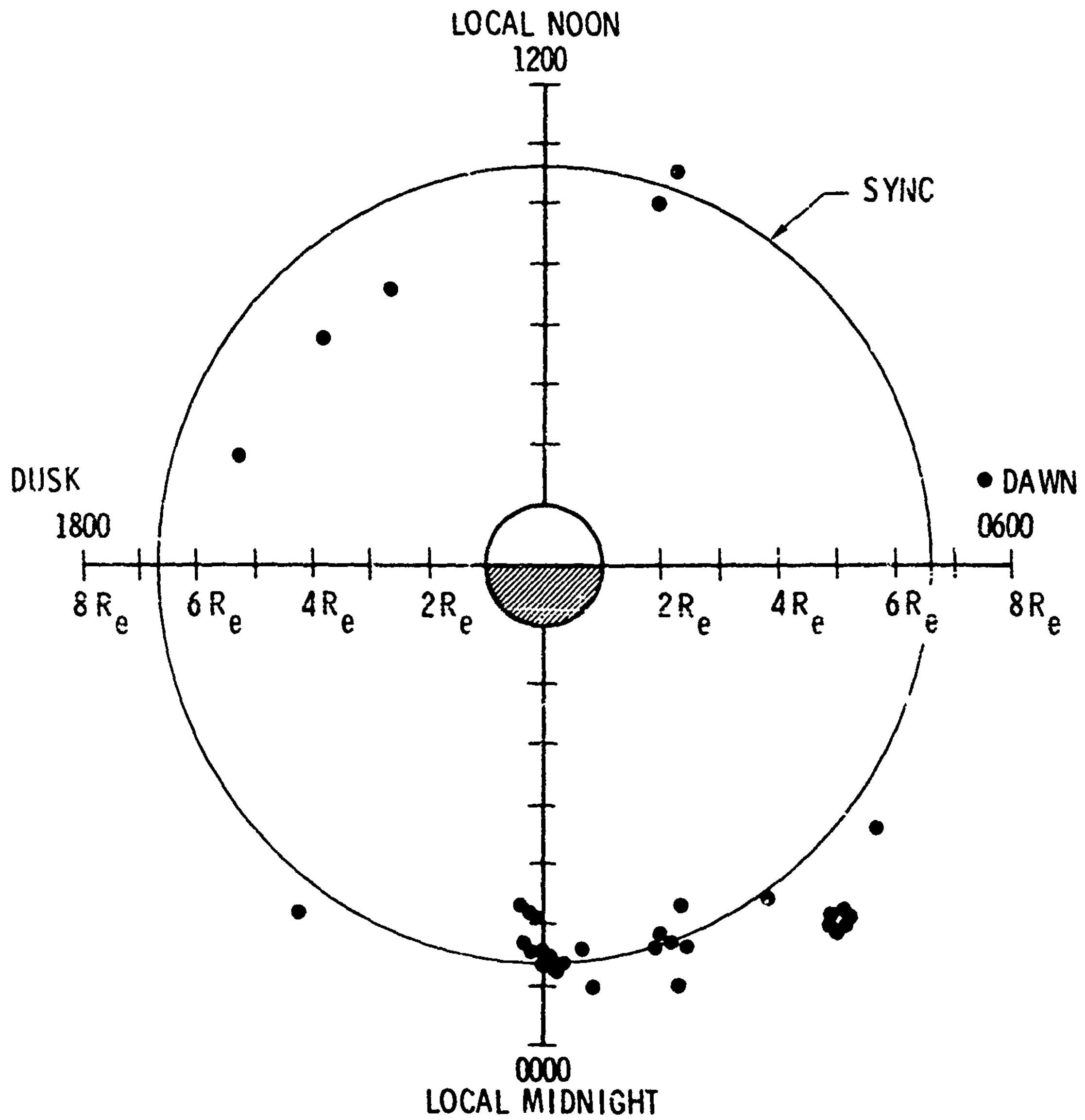

Fig. 10. Satellite Location in Radial Distance and Local Time when Discharges were Detected on The Aerospace Corporation Pulse Monitor (after Ref. 14)

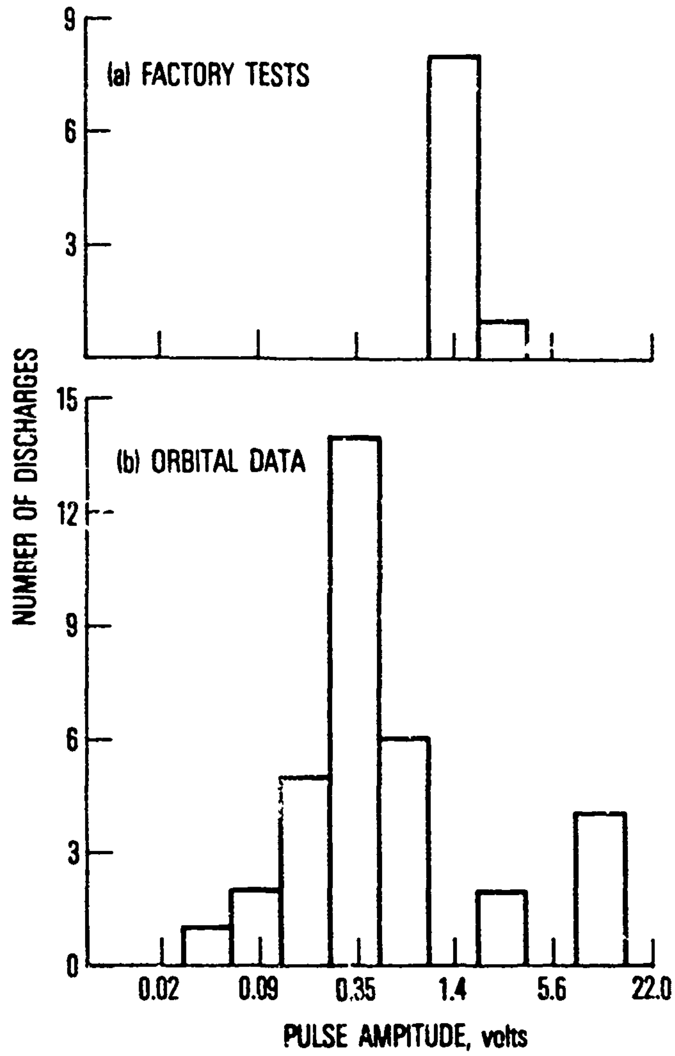

Fig. 11. Histograms of Pulse-Amplitude Distribution. (a) Discharges measured during preflight, factory, electrical-discharge tests. (b) Discharges measured on orbit.

shown; a good correlation is seen between the two data sets. This comparison reinforces the belief that the discharges are caused by a potential buildup to breakdown levels during charging events.

The SCATHA satellite also carried a discharge-pulse analyzer, part of the CEEA, to measure the occurrence and temporal profile of discharges by means four different sensors that were duty cycled. A comparison of the surface-charging data at the time of observed discharges showed that not all discharges were correlated with surface charging. Figure 10 shows a local time-distance plot of the discharges detected with this Aerospace experiment (Ref. 14). The discharges detected in the prenoon to dusk sector were not associated with surface charging; it is likely they resulted from bulk charging, as discussed above for Teflon and elsewhere (Refs. 10, 14, 19, 29, 33, 35, and 36).

The amplitude distribution of the pulses measured by the Aerospace experiment are compared with the amplitudes resulting from the MIL-STD 1541 electrostatic discharge tests at the SCATHA satellite contractor's factory (Fig. 11). Only pulses above 1.27 V on a spacecraft harness wire, terminated in 50 ohms, could be detected in the factory tests. Most of the discharges detected on SCATHA had amplitudes less than or equal to the test amplitudes. The two largest pulses observed to date on orbit were well above the factory test amplitudes and indicate that the MIL-STD 1541 test is not a worst-case test of the expected on-orbit conditions. Some modification of this test is probably in order.

To provide some idea of the discharge signal's shape in the time domain, the temporal profile of three pulses measured during a charging event in April 1981 are shown in Fig. 12. The points are taken at 15-nsec intervals. A function of the form

$$V = V_0 + \Sigma V_i e^{-k_i t} \cos(2\pi f_i t + \phi_i) \qquad (1)$$

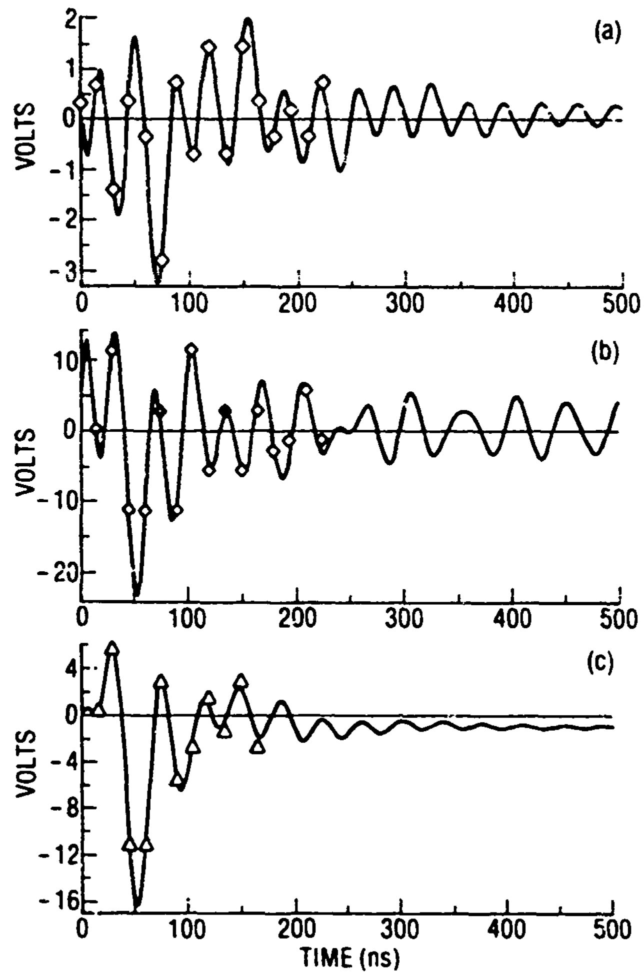

Fig. 12. Pulse Shapes Measured for Three Large Discharges Observed on 23 April 1981 (after Ref. 14)

was fit to the data (Ref. 14). This fit allows us to extract the characteristic frequencies plus some estimate of maximum amplitude. The curves are not identical. From the limited data-set available with the 15-nsec resolution, it is not possible to characterize the discharge pulses. At best, it can be stated that the dominant frequencies tend to fall in the 5 to 32-MHz range and the peak amplitudes vary from ~0.08 to 30 V (Refs. 12, 13, and 14). There is evidence for much "ringing" in the pulses (Fig. 12). The same results were obtained when the lower time-resolution data were examined (Ref. 13).

Several events have been studied wherein the surface charging levels, spacecraft-structure charging levels, and occurrence of discharges were compared (Refs. 8, 11, and 14). For example, in Fig. 13 the data were taken during a charging event on 23 April 1981. The relationship between the spacecraft potential (top panel), the Kapton potential (bottom panel) and discharges (arrows) is shown.

In each case studied, the discharges generally occur at times of maximum voltage stress, as indicated by rapid potential changes. These times also correspond to the rapid change in the plasma environment and changes in the illumination of the spacecraft or some of its surfaces.

In one case (Ref. 12), a succession of six pulses were observed at the same satellite spin phase over a period of 12 min. The satellite was sunlit and it was concluded that the rotation of one region into or out of the sunlight was the "trigger" for the discharges. Examination obtained so far of all other discharges in sunlight did not show that a clear preference for a particular spin phase existed on SCATHA. In other cases, the discharges are clearly associated with the satellite entrance into and exit from eclipse (see Fig. 13). This emphasizes the fact that solar UV plays a strong role in the generation of high electrical stress and discharges.

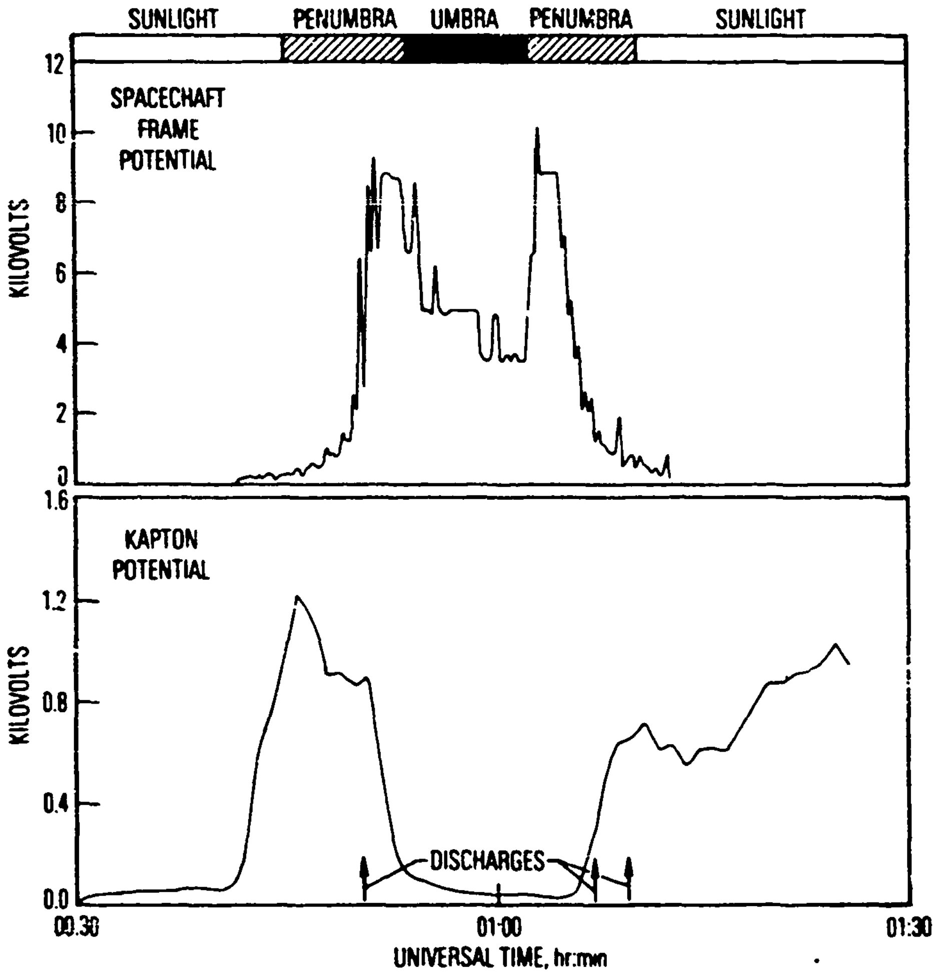

Fig. 13. The 23 April 1981 Charging Event. The top panel shows the SCATHA satellite position relative to the eclipse time, and the temporal history of the spacecraft frame potential relative to the plasma. The bottom panel shows the Kapton potential with respect to the satellite frame and the times of the three discharges detected during the event (after Ref. 14).

IV. SUMMARY

The plasma and solar UV environment act on dielectric materials to produce effects that were not clearly understood prior to the SCATHA satellite program. Previously, only the thermal and optical properties of Kapton and Teflon materials were of concern to engineers. With the knowledge that these dielectrics charge up in the space plasma and can discharge, causing spurious system responses (Refs. 10, 20, 30, and 31), it became important to consider their electrical properties. The pre-SCATHA laboratory tests did not uncover all the important properties of such materials. The orbital data bore out some of the laboratory results but showed differences from others. Also, the relationship between surface charging and the occurrence of discharges on a satellite were not known.

The charging of the quartz fabric to high levels, during impulsive charging events lasting minutes to hours, was a surprise. The fact that the material responded in the same way in the laboratory, when the proper simulation was performed, showed that the "worst-case environment" testing normally used can be misleading. In the future one must be careful to verify first that the worst-case test conditions do not hide the response being tested for.

The testing of the Teflon materials before launch did not uncover the bulk charging of the material by energic electrons (>50 keV), because such energies were not used in the tests and only surface charging was considered. The SCATHA results show that bulk charging can be equally important for Teflon. Recent calculations by Reagan et al. (Refs. 28 and 29) show that most of the Teflon response is to energetic electrons. In fact, a significant number of discharges on the SCATHA satellite are suspected of being the result of bulk charging (Refs. 13 and 14), as are some anomalies on other spacecraft (Ref. 33). At the time of early SCATHA satellite data, some test results became available which indicated that energetic electrons can penetrate into the interior of spacecraft and charge highly resistive dielectrics there. Then arcing can occur and cause system upsets (Refs. 19 and 35). Thus, bulk charging of highly resistive materials must be considered wherever exposure to intense fluxes of very energetic electrons is possible.

The permanent conductivity enhancement of Kapton by solar UV exposure could reduce charging of vehicle surfaces composed of this material, especially in high-altitude (>500 km) orbits. The question of whether the oxygen densities experienced in low-altitude orbits ($<10^{10}$ cm^{-3} above 200 km altitude) could quench the photo-induced conductivity has not yet been studied and may be important there.

The number of discharges observed by SCATHA is fewer than would have been expected from an analysis of much of the laboratory test data and the levels of surface charging observed. The difference can probably be ascribed to the fact that the laboratory testing, which generated large numbers of discharges, was carried out with monoenergetic beams and beam currents (i.e., $\gtrsim 10$ namps/cm^2) much higher than the currents experienced on orbit (~ 0.1 namps/cm^2). For example, when the electron gun on the SCATHA satellite (Ref. 31) was operating in such a way that large currents were emitted, causing the satellite to charge, then many discharges were seen (Refs. 12 and 13). These "driven" discharges also had a different character than the natural ones (Ref. 13).

The few natural discharges observed have a local time distribution reminiscent of the satellite operational anomalies (Ref. 20) that have occurred over the years. The discharges that occurred while SCATHA was <u>not</u> experiencing charging (~15% of events) support the recent contention that bulk charging of highly resistive materials is also an important factor (Refs. 29, 33, 35, and 36). The remainder of the discharges show a good correlation with the regions of high probability of charging.

Finally, while most of the discharges observed had amplitudes smaller than experienced during the MIL-STD 1541 tests, the observation of discharges with significantly larger amplitudes indicates that the satellites built to meet this test specification will still experience operational anomalies related to charging.

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